JOREK CONTRIBUTIONS TO THE PREDICTIVE UNDERSTANDING OF TRANSIENT PHENOMENA IN FUTURE TOKAMAKS AND STELLARATORS

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For ITER and DEMO size tokamak or stellarator devices, robust stationary operation and protection from damage relies on the avoidance, control or mitigation of large-scale transient plasma instabilities and needs to be based on reliable predictive understanding. This contribution summarizes the research conducted worldwide since the previous IAEA FEC using the JOREK 3D non-linear hybrid fluid-kinetic code in this area. Entirely new high-fidelity models were developed including a unique 3D full-f particle-in-cell (PiC) treatment of runaway electrons (REs), an enhanced stellarator magneto-hydrodynamic (MHD) model, a full-MHD coupling to the resistive wall code CARIDDI, and an advanced kinetic treatment of neutrals and impurities in scrape-off layer and pedestal. Work on the interpretative and predictive modelling of disruptions including disruption consequences, mitigation, runaway electrons and vertical plasma instabilities is summarized in Section 1. Research regarding pedestal, scrape-off layer and divertor is addressed in Section 2. The increasing capabilities and contributions to stellarator research are shown in Section 3 and further research areas including numerical methods are shown in Section 4.

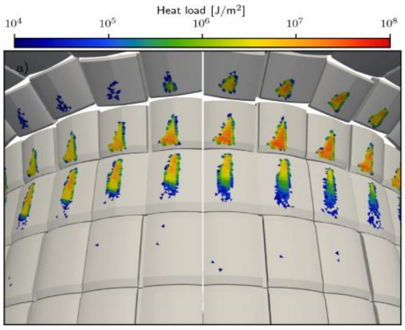

Fig. 1: *Prediction of the RE deposition to wall structures during a 3D MHD induced termination event [H Bergström, PPCF 2024]*

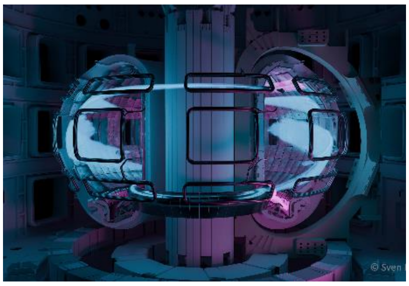

Fig. 2: *Tungsten impurity transport in ITER with applied resonant magnetic perturbations, analyzed by virtual diagnostics [SK Korving, PhD thesis]*

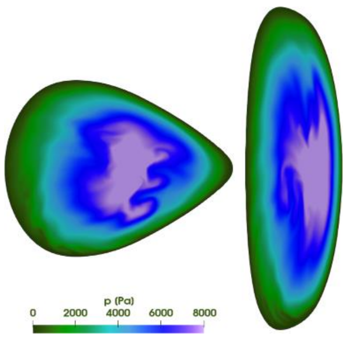

Fig. 3: *Wendelstein 7-AS simulation of the non-linear dynamics of pressure driven instabilities [R Ramasamy, submitted to NF]*

1.DISRUPTIONS, VERTICAL INSTABILITIES, RUNAWAY ELECTRONS AND MITIGATION

Substantial work went into the simulation of disruption mitigation by shattered pellet injection (SPI) covering JET, ASDEX Upgrade (AUG), KSTAR, and ITER. Different injection parameters were studied (pure deuterium and mixed compositions, single and multiple injections, different injection velocities, different shattering angles and shard numbers), direct experiment comparisons were carried out and SPI induced radiation loads onto the ITER first wall were predicted. A dedicated study addresses the challenge of accurately capturing the plasmoid drift dynamics and related resolution requirements. The existing eddy current coupling with CARIDDI was extended to the full MHD models of JOREK. Extensive experimental validation studies in JET and AUG revealed the mechanisms that reduce the vertical wall force upon impurity injection, driven by the current decay and the vertical motion following the thermal quench. Predictive simulations for ITER and other devices were carried out. Direct experimental validation for the RE beam generation and termination progresses. The vertical motion of runaway electron beams in ITER and an EU-DEMO concept were studied predictively for different mitigation scenarios and a less efficient current conversion was found compared to studies neglecting vertical instabilities. For these machines, also the termination by a burst of 3D MHD activity and the wall deposition of the REs was studied under varying assumptions providing the most detailed predictions available to date (**Fig. 1**). Wall damage analysis based on this data is in progress. Similar work for the DTT tokamak under construction in Italy is on the way. While the previous work relies on a RE fluid model where the phase space is not resolved, novel full-orbit and drift or gyrokinetic full-f PiC models for REs were developed providing a particularly accurate description of the coupled MHD-RE system, albeit at substantial computational costs. These new models were carefully verified by comparisons to analytical predictions of the RE induced Grad-Shafranov-like shift and to the growth rates of tearing modes in a RE beam. A first application of the novel models to a RE beam termination scenario was demonstrated and a dedicated study of linear and non-linear MHD dynamics in a RE beam is ongoing. Hot-tail, nuclear and avalanche sources for this hybrid fluid-kinetic model are in development. Ongoing work addresses the self-consistent halo current coupling with CARIDDI for accurate lateral force predictions as well as disruption/RE studies with advanced kinetic descriptions of neutrals and impurities.

2.PEDESTAL, SCRAPE-OFF LAYER AND DIVERTOR

Building up on earlier work for regimes without large edge localized modes (ELMs), access to quiescent H-Mode in the HL-3 tokamak and its non-linear behaviour was studied predictively. Detailed time dependent studies of detachment were carried out using the further enhanced hybrid fluid-kinetic SOL/divertor models with neutral deuterium and impurity PiC treatment. Using the same model, burn-through by enhanced transport of fluctuating MHD modes is under investigation for an AUG small-ELM scenario and time-resolved simulations of an X-point radiator were performed for AUG, qualitatively reproducing many experimental observations including the formation, vertical motion, loss, and the transition to a MARFE. Resonant magnetic perturbation fields as used for ELM mitigation and suppression in various devices, were studied for the HL-2A device. In addition, joint work between the AUG experimental team and the JOREK community for the first-time provided direct evidence of the formation of magnetic islands at the top of an H-mode pedestal. Tungsten sputtering and transport was studied in ITER RMP plasmas (**Fig. 2**) and EAST with different models. Future work will include surrogate model developments for ELM-free/small-ELM scenarios suitable for use in transport codes or flight simulators.

3.STELLARATOR

The MHD stellarator models were extended in several ways, in particular by including the parallel velocity component and implementing ExB background flows that can act stabilizing onto MHD modes. Integration of various hybrid fluid-kinetic extensions is on the way. Based on such work, pressure driven instabilities in Wendelstein type devices were investigated aiming to reproduce soft beta-limits in simulations and assessing the non-linear dynamics following Mercier unstable conditions (**Fig. 3**). Other work addresses core crashes following electron cyclotron current drive induced current distributions and an accurate modelling of pellet ablation and material assimilation in direct comparison with theoretical predictions. Future work will address the island divertor geometry, edge stability, and SOL/divertor questions of different stellarator concepts.

4.FURTHER RESEARCH AREAS

The flux-pumping mechanism that can prevent sawteeth via a self-regulating dynamo loop voltage was studied at realistic experimental parameters of AUG over the current diffusion time scale, quantitatively reproducing observations. Via parameter and source variations, input is generated for a surrogate model and extrapolation to future devices. With the electrostatic gyrokinetic full-f PiC model, ITG/TEM saturated turbulence was studied for RMP scenarios and positive/negative triangularity in realistic X-point geometry. Smaller time-space correlation of density fluctuations and stronger zonal flows were found at negative triangularity explaining lower turbulence amplitudes and better confinement at negative triangularity. An electromagnetic model and enhanced collision operators are in development. Substantial work is invested in porting the code to accelerated HPC platforms including matrix construction, iterative solver, and kinetic pushers. Model order reduction approaches are followed for the coupling to CARIDDI and machine learning methods for the solver/preconditioner are tested. Tools for exporting JOREK data to and importing plasma scenarios from IMAS databases were consolidated.